ARTag, a fiducial marker system using digital techniques

Mark Fiala
National Research Council of Canada
NRC 1200 Montreal RD, Ottawa, Canada K1A-0R6
mark.fiala@nrc-cnrc.gc.ca

Abstract

Fiducial marker systems *consist of patterns that are mounted in the environment and automatically detected in digital camera images using an accompanying detection algorithm. They are useful for* Augmented Reality *(AR), robot navigation, and general applications where the relative pose between a camera and object is required. Important parameters for such marker systems is their false detection rate (*false positive rate*), their* inter-marker confusion rate*, minimal detection size (in pixels) and immunity to lighting variation.* ARTag *is a marker system that uses digital coding theory to get a very low false positive and inter-marker confusion rate with a small required marker size, employing an edge linking method to give robust lighting variation immunity.* ARTag *markers are bi-tonal planar patterns containing a unique ID number encoded with robust digital techniques of checksums and forward error correction (FEC). This proposed new system,* ARTag *has very low and numerically quantifiable error rates, does not require a greyscale threshold as does other marker systems, and can encode up to 2002 different unique ID's with no need to store patterns. Experimental results are shown validating this system.*

1. Introduction

Designing markers to add to the environment for robust detection in camera and video imagery is a computer vision application useful to situations where a camera-object pose is desired such as *Augmented Reality* (AR), position tracking, photo-modeling and robot navigation. 2D planar patterns can be added to the environment and recognized in the camera images. A 2D planar marker system consists of both a set of planar patterns and the associated computer vision algorithms to recognize them in an image. *ARToolkit* [5, 7] is a popular such system which contains a 2D planar fiducial marker system, it is used in many Augmented Reality applications and is used frequently in this paper for a basis to evaluate ARTag.

Metrics describing performance of fiducial marker systems are; 1) the *false positive* rate, 2) the *inter-marker confusion* rate, and 3) the *false negative* rate. The false positive rate is the rate of falsely reporting the presence of a marker when none is present. The inter-marker confusion rate is the rate of when a marker is detected, but the wrong id was given, *i.e.* one marker was mistaken for another. Finally, and possibly the least serious, is the false negative rate, where a marker is present in an image but not reported. The false positive and false negative rates are at odds with one another, and represent a trade-off between missing a marker and seeing a non-existent one. Another metric is 4) the *minimal marker size* which is the size in pixels required for reliable detection. The smaller the marker is allowed to be in the image, the larger the usable range from the camera the marker system can be used.

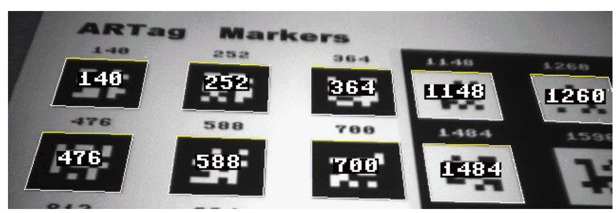

Figure 1. *Markers detected in an image. Overlaid white border and ID number show automatic detection. ARTag markers are bi-tonal planar marker patterns consisting of a square border and a 6x6 interior grid of cells representing logic '1' or '0'.*

Other measures of fiducial marker system performance, although not quantitatively measured herein, are; 5) the *immunity to lighting conditions* and 6) detection jitter. Detection jitter addresses how much "shaking" there is in the image position of the detected markers, a factor important in AR systems.

ARTag is a bi-tonal system containing 2002 planar markers, each consisting of a square border and an interior region filled with a 6x6 grid of black or white cells. 1001 of ARTag markers have a black square border on a white background, and vice versa for the other 1001. Fig. 1 shows some example ARTag markers. The associated algorithm for detection first locates quadrilaterals which may be perspective views of the marker border, then the interior is sampled into 36 binary '1' or '0' symbols. Further processing is in the digital domain providing a non-linear response giving very low *false positive* and *inter-marker confusion* rates. With ARTag, the probability of falsely identifying one marker for another, or a piece of the background as a marker, is a probability of $< 0.0039\%$. Fig. 1 shows ARTag markers being detected in an image.

ARTag is available to download for evaluation at [1].

2. Planar Marker Systems

Many of the practical machine vision systems used in industry use two dimensional patterns to carry information in a manner similar to the ubiquitous bar code seen on consumer products. The purpose is to carry information, not to localize as is needed for applications such as augmented reality. The US Postal Service uses the *Maxicode* marker to convey shipping information (Fig.2). *Data matrix* and *QR (Quick Response)* are two other examples designed to contain information are used in industrial settings for part labelling (also shown in Fig.2). The above three all use or have provision for error correction methods to recover the data when some of the bits are incorrectly read. ECC200 [2] is a standard for *Data matrix* 2D patterns and uses Reed Solomon error correction, which can recover from situations where part of the information read from the pattern is corrupted. Data Matrix and QR are used for *Direct Part Marking* (DPM) to identify and convey information along an assembly line.

Datamatrix, Maxicode and QR all have a common thread of encoding data using binary values for reflectance, the pattern is typically bitonal reducing the decision made per pixel to a threshold decision. This reduces the lighting and camera sensitivity requirement and removes need for linearization of the signal (*i.e.* no attempts are made to identify shades of grey). Another component is that of redundant information allowing for error detection and correction to increase the overall success rate. Error detection and correction is something not seen as much in computer vision as in other fields such as telecommunications, and is a well understood class of methods to statistically improve the data integrity rate to a very reliable level.

In general, Datamatrix, Maxicode and QR are useful for encoding information, but are not as useful for fiducial marker systems for two reasons. Firstly they are not intended for, and won't function well, in situations with large field of views and the perspective distortion that introduces. And when detected do not provide enough image points for 3D pose calculation. Datamatrix can only adjust for affine warping by using the 'L' shaped locator, *i.e.* with 3 points instead of the 4 required to correct for perspective distortion. Secondly they typically require a large area in the image limiting the range at which the markers can be used.

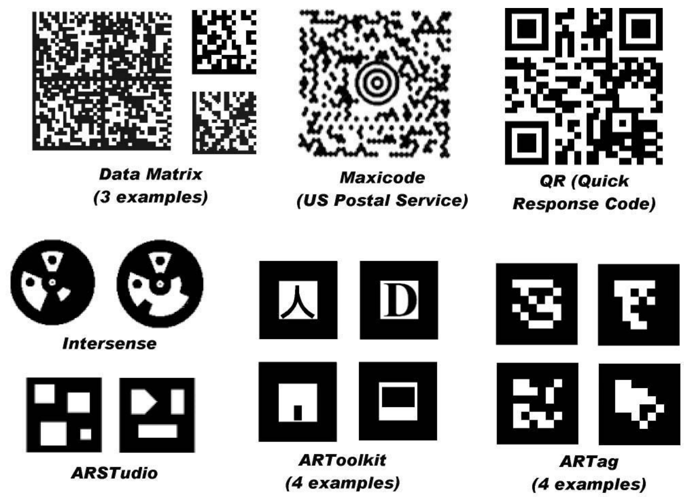

Figure 2. *Several planar pattern marker systems. Data Matrix, Maxicode and QR are industrial systems used for carrying data. The circular Intersense markers are used in position tracking. ARStudio and ARToolkit are patterns designed specifically for AR. ARTag is the new marker system introduced in this paper.*

Locating and identifying simple planar patterns is also used by several photogrammetry, position tracking, and augmented reality systems where less information is carried in the marker, typically only enough to identify it from others. In applications such as photogrammetry, the size of the marker is an issue. In general, the less dense the information is in the marker, the less the minimum pixel requirement is and as a result, the greater the range of distance that the marker can be from the camera.

Small markers can be made by encoding a ring of segments around a circular dot [8]. Several commercially available circular fiducial marker systems exist using a single broken annular ring around a circular dot such as Photomodeler's "Coded Marker Module" [3]. Naimark and Foxlin [9] describe a system extending the number of rings. The number of possible markers is limited, the camera resolution will limit the number of segments that the annular ring can be broken into. The false positive and inter-marker con-

[1] http://www.artag.net
[2] http://www.eia.org
[3] http://www.photomodeler.com

fusion rates are not reported for these systems but due to the small number of digital bits that can be encoded, they will suffer from a high rates or small library sizes (if some bits are used for redundancy) or most likely both. For AR and other applications where not just the location but the pose must be determined, these markers are not as useful due to the difficulty in determining the plane they lie in.

For camera-pattern pose to be determined from a single image, at least four point correspondences need to be found, ARTag, ARToolkit [5] and ARSTudio use four points on the periphery of the pattern.

Zhang [11] and Claus [3] perform a survey of several fiducial marker systems including ARToolkit with respect to processing time, identification, image position accuracy with respect to viewing angle and distance. ARToolkit is popular because it is simple, relatively robust, and freely available. ISMAR [1] is an augmented reality conference where many applications use ARToolkit.

ARToolkit markers consist of a square black border with a variety of different patterns in the interior. The quadrilateral black outline is used to calculate a homography to define a sampling grid inside the pattern which is sampled to provide a 256 (or 1024) element feature vector which is compared by correlation to a library of known markers. ARToolkit outputs a so called *confidence factor* which is the result of a normalized vector dot product between the sampled 16x16 (or 32x32) vector and the stored prototypes. Presence of a marker is simply determined by a threshold value on this confidence value.

ARToolkit is useful for many applications, but has a few drawbacks. The use of correlation to verify and identify markers causes high false positive and inter-marker confusion rates. The user typically has to capture prototypes of each marker as seen with the camera and lighting of their application, plus adjust the greyscale threshold in a trade off between these two rates and the false negative detection rate. Only markers whose borders can be defined by this fixed threshold can be found. Also, the uniqueness of the markers deteriorates as the library size increases. The processing time also rises as that the normalized center region of each quadrilateral must be correlated with all marker prototypes in the library. To address the four possible rotations and possible differences in lighting, twelve prototypes are stored for each marker. Owen [2] proposes an ARToolkit library based on spatial frequency components to extend the library but ARToolkit's inter-marker confusion rate still restricts the library size.

3. ARTag

ARTag is a planar pattern marker system that has 2002 markers, with improved performance to ARToolkit in identification and verification, a larger library, and no need of pattern files. The main problem with ARToolkit is that it can often falsely detect markers where there are none, and frequently confuses them. The paradigm of using a square border with an interior pattern is maintained in ARTag, but the processing of the internal pattern is replaced with a digital approach.

The feature of ARToolkit that, in the eyes of this author, contributing most to its functionality is the use of only black and white for the border, using only two extremes of reflectance in a marker allows many issues of image capture and greyscale non-linearity to be avoided. This binary decision is extended in ARTag from just defining the border to defining the inner pattern as well.

The ARToolkit square border is useful for AR since it has four prominent corners. Four points allow the full extraction of the 6 degree of freedom (DOF) of the relative marker to camera pose (assuming the camera focal length is known). ARTag was designed to contain the successful elements of ARToolkit and Datamatrix, and take the best of both and make a minimal but robust system for AR.

Several ARTag markers are shown in Fig. 1. The main characteristics are a square border of either polarity (white on black or black on white) and a 6 x 6 square grid dividing up the interior. The whole marker is 10 x 10 units, with a border of thickness 2 units leaving 36 cells in the interior to carry information. Each cell is only black or white and carries one bit of digital data. Thus a 36-bit word can be extracted from a camera image of the marker once the boundary is determined.

3.1 Quad Detection

Quadrilateral contours are located in the image which may belong to the outside border of a marker. They are found in ARTag with an edge based method, edge pixels are thresholded and linked into segments, which are in turn grouped into "quads". The four corners of the quad boundary are used to create a homography mapping to sample the marker interior. Fig. 3 shows an image, its extracted line segments, quads, and quads in which ARTag marker codes were found in the interior.

The edge based approach gives some performance improvement over the greyscale region thresholding approach of other systems such as ARToolkit. In ARToolkit, groups of connected pixels below a specified threshold are found, and those possessing a quadrilateral boundary are used as potential markers. Having a spatial derivative of greyscale intensity threshold instead of a simple greyscale intensity threshold allows markers to be found under less controlled lighting conditions. Indeed, the 'white' level of one marker edge may be darker than the 'black' level of the other side and the marker still be detected.

Another advantage to ARTag's edge based approach is

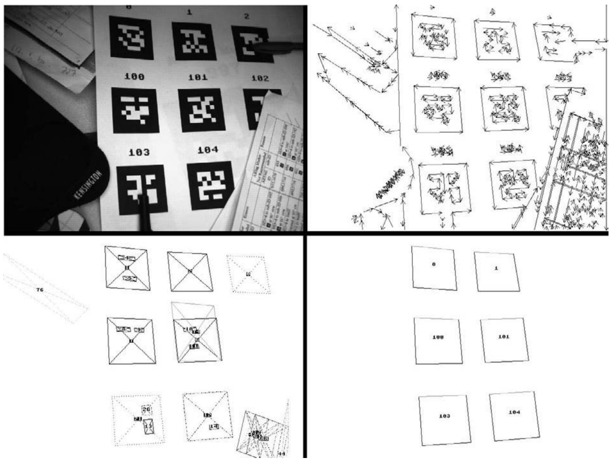

Figure 3. *Quad Extraction: finding ARTag markers. (Upper left) original image, (Upper Right) straight line segments found in image, (Lower left) line segments grouped into quadrilaterals, (Lower right) ARTag markers found from quadrilaterals whose interiors contained a valid ARTag code.*

the ability to still detect marker outlines in the presence of occlusion. In Fig. 3, two of the markers (ID's 103, 104) have a side broken or a corner missing but are still detected by heuristics of line segments that almost meet. Fig. 3 (lower right) shows the occluded quads drawn with dotted lines indicating that they were not obtained from the perfect grouping of four segments.

To further reduce the false negative rate, ARTag searches for quads at three scales. The line segment extraction and grouping into quads is done on the original image size, on a resampled version of half the width and height, and on that of a quarter size. This allows the detection of borders which may be blurry and not have an spatial derivative above the threshold. [4]

4 Digital Processing

Once quadrilateral border contours have been located, the internal region is sampled with a 6 x 6 grid and assigned digital symbols '0' or '1'. The threshold applied is derived from the intensities found around the quad border. All subsequent processing to verify and identify the marker is performed digitally. Four 36-bit binary sequences are obtained from the 2D 6 x 6 digital symbol array, one for each of the four possible rotation positions. Only one of the four sequences may end up being validated in the decoding process. The 36-bit binary sequence encoded in the marker encapsulates a 10-bit ID using digital methods. The extra 26 bits provide redundancy to reduce the chances of false detection and identification, and to provide uniqueness over the four possible rotations. The *Cyclical Redundancy Check* (CRC) and *forward error correction* are digital methods used to identify if the 36-bit code is part of the ARTag marker set, and to extract its ID.

These methods use a digital algebra called *GF-2* or *Modulo-2* mathematics and involves concepts of addition using logical XOR, convolution and deconvolution operators, and *generating polynomials* which are prime numbers in this base 2 number system. It is beyond the scope of this paper to explain other than to describe that in practice one manipulates short binary symbol sequences with various operators, the most important one to ARTag marker decoding is the deconvolution/division operator. The reader is directed to [10], digital communications and storage texts, and standards documents for more information. In two stages of decoding ARTag markers, digital codes are divided by specially chosen binary polynomials where the dividend and remainder are both used.

The system can be abstractly described as a communication system, where a 10-bit ID is attempted to be sent through a medium of image capture to be received by the ARTag vision software. The creation of a marker pattern from an ID is the encoding phase, and the recognition of an ID from the extracted 36-bit code is the decoding phase.

There are three main stages for encoding when creating the 2D pattern to mount in the environment, with their operations performed in reverse when finding ARTag markers. The digital encoding operations are shown in Fig. 4 below.

The printing of the marker pattern, the reflectance of the marker, lighting, other objects in the scene, light capture and digital image formation by the camera including noise, and perspective pose of the marker all constitute the "communications medium". After a 6 x 6 grid of binary symbols is extracted from the image, the digital decoding steps outlined in Fig. 5 are performed and the verdict of ARTag marker presence or not is decided, and the ID reported if present.

The XOR operation is used to scramble the codes a bit since it's expected that users would use the lower numbers 0,1,2,... etc and to make the ID of 0 usable. The CRC-16 polynomial (also known as CRC-CCITT in the fields of data storage and communication) is $x^{16} + x^{12} + x^5 + 1$ and is applied by convolving the XOR'd ID with the binary string *10001000000100001*. The deconvolution in the decoder is similar to a division operation yielding a dividend and remainder. The remainder must be 0 otherwise the code is considered not to be from an ARTag marker, only $\frac{1}{2^{16}}$ of the possible binary sequences pass this test protecting against

[4] To speed performance on lower processing power systems, the quad detection can be turned off for the full resolution speeding up ARTag by about 3-4 times.

random codes found from quadrilateral objects in the camera view that are not ARTag markers.

The forward error correction (FEC) decoding block is the most sophisticated digital processing component of the ARTag system and allows several erroneous bits in the input 36-bit code to be detected and repaired. This increases the false positive rate but improves the false negative rate by recognizing codes that are close to a correct code, that are likely an ARTag code with a sampling error due to sources such as an imperfect threshold, misalignment of the detected quadrilateral border, specular reflections inside the pattern, partial occlusion, and general image noise.

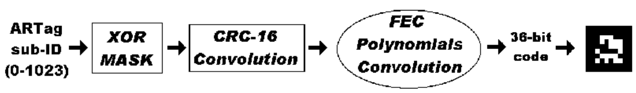

Figure 4. *Digital encoding process : creating ARTag markers. A sub-ID number (the lower 10 bits of the ARTag ID) is converted to a 10-bit binary sequence which goes through several stages to produce a 36-bit binary sequence which is encoded in the marker as white and black cells.*

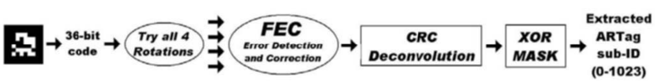

Figure 5. *Digital decoding process : confirming and identifying ARTag ID's in the binary pattern from the interior of an ARTag marker. The binary pattern from the marker as seen in the camera image is converted into four possible 36-bit codes for each possible rotation. Each code passes through the FEC stage which can detect and correct some bit errors, the result is then analyzed by a CRC checksum-like procedure to verify if it belongs in the ARTag marker set. If it is, a payload 10-bit binary number (sub-ID) is extracted and combined with the border polarity and reported as a located ARTag marker.*

Two ARTag ID numbers, 682 and 1706, are absent from the ARTag marker library reducing the library size to 2046. The reason for this is that the sub-ID 682 is a degenerate case that leads to a 36-bit code containing all 0's. This would translate to a fully black or white interior which will be frequently falsely detected in the environment. The library is further reduced to 2002 markers by the removal of 44 ID's to improve the inter-marker confusion rate as described in [4].

4.1. False Positive Marker Detection

One failure mode of a marker detection system is when a marker is erroneously reported when it does not exist, a high false positive detection rate is one drawback of the popular ARToolkit marker system.

While ARToolkit identifies markers by correlation, ARTag uses digital techniques. With ARTag the internal pattern is sampled and processed as a digital code and has a low false positive rate which can be mathematically described. $1001 * 4 = 4004$ of those digital codes map to a correct ARTag marker viewed from one of four orientations. There are 36 points sampled within the pattern, giving $2^{36} = 68.7$ billion digital codes from an arbitrary randomly filled quadrilateral. With N=2 (N=number of bits the FEC can correct, N=2 in the first version of ARTag released), each valid ARTag 36-bit code would be mapped from $1 + 36 + 36 * 35/2 = 667$ 36-bit codes, yielding $4004{\cdot}667 = 2.67$ million 36-bit pattern interiors which would cause ARTag to report the presence of a marker. So the probability of a false positive detection from a random 36-bit number is $\frac{2.67 \cdot 10^6}{68.7 \cdot 10^9} = 3.9{\cdot}10^{-5} = 0.0039\%$, or about one in 26,000. Therefore a non-marker quadrilateral has a 0.0039% chance of producing a false positive marker event assuming equal likelihood of pattern interiors (which is not usually the case giving an even more rare probability). Most natural (non-marker) quadrilaterals in the environment are solid black, or contain much less entropy than the ARTag pattern interiors.

A comparison experiment was performed with several image sequences which do not contain any ARToolkit or ARTag markers to collect statistics on false positives (ARToolkit was the only modern marker system made available to the author, an ideal study would also test the Intersense circular fiducials [9] and the markers from the ARVIKA project [5]). Both the ARToolkit code and the ARTag library were compiled into one program so that they both saw the exact same image frames. Table 1 shows the results for marker detection with video from several cameras which were moved around our lab in which no ARToolkit or ARTag markers were present, thus any marker detection is a false positive. A movie was also used as an image sequence in order to get more random and varied imagery than video footage from our lab.

Looking at the results in Table 1, one could suggest simply raising the threshold c.f. factor to 0.90 and thus avoid all false positives for ARToolkit. However, with the same conditions, the c.f. had to be lowered to 0.75 to obtain a practically usable false negative rate.

No ARTag false positives were seen in any of the experiments, or noticed when using the system, however the probability is still non-zero, about $\frac{1}{26000}$ as mentioned above.

[5]http://www.arvika.de/www/index.htm

Imagery		ARToolkit				ARTag
Seq-uence	Num. Frames	c.f.= 0.50	c.f.= 0.70	c.f.= 0.80	c.f.= 0.90	
A	2723	175	15	9	3	0
B	3514	235	9	3	3	0
C	3318	401	70	0	0	0
D	1450	135	88	70	27	0
E	1318	68	14	3	0	0
F	1318	68	14	3	0	0
G	2893	410	3	0	0	0
H	215625	7917	408	112	0	0

Table 1. Comparison between false positive detection rates between ARToolkit and ARTag in several image sequences. Different cameras were moved around a room devoid of either markers so that all detections would be false positives. A single common set of ARToolkit pattern files were used. Note that no false positive ARTag markers are declared in any of the frames. A-G are tests with various cameras aimed around a lab scene, H is the movie "Bladerunner" (Ridley Scott 1982).

However, this is the probability after a quadrilateral has been found assuming equal likelihoods of all 36-bit codes. Whereas most quadrilateral shapes in the environment are mostly all dark or all white, and will likely not have a full frequency content as the ARTag patterns do (the pseudorandom nature of the convolution codes used give a wide use of spatial frequencies).

4.2. Uniqueness of Markers: Reducing Inter-Marker Confusion

As well as a low false detection rate, a good marker system should have a low rate of confusion between markers. The user should have a high confidence that one marker won't be mistaken for another. In the real world one cannot have 100% but with proper marker system design the rate that this occurs can be minimized, ideally to very low levels that don't appear in practice. Owens *et al.* [2] explores the similarity between ARToolkit markers with the *Mean Squared Error* (MSE) approach and proposes a library of markers based upon spatial frequencies in an attempt to address this problem.

The inter-marker confusion rate for ARTag can be analyzed by considering the probability of mistaking one code of digital symbols for another. A measure of how easily two binary codes can be confused with each other is to calculate the *Hamming distance*[6], which is simply the sum of the differences between two digital sequences (eg.the Hamming distance between the sequences *01001* and *00011* is 2). The probability of an inter-marker confusion event can be calculated using knowledge of the Hamming distances within a marker set between all markers taking rotation and optionally mirroring into consideration.

The probability that a digital code can be mistaken for another in a set of codes is given by a summation of the probabilities that the given marker can be falsely recognized as each of the other codes in the set. To find the probability that a given marker can be mistaken for any other code in the set, one adds four (for rotation only) or eight (rotation and mirroring) probabilities for each marker. The probabilities can be added together by grouping together all the cases of equal Hamming distance and calculating the probability from the total Hamming distance histogram.

To calculate the probability $P(\neq A)$ that a marker A can be mistaken for another (in the set used in a system), the bit error rate p in Eqn.1 can be used. $p(n)$ and $q(n)$ are the probability of n bits being falsely and correctly detected, respectively. If the bit errors are uncorrelated and independent events, then the probability of n bits toggling falsely is $p(n) = p^n$ and not toggling is $q(n) = (1-p)^n$ allowing us to rewrite the probability as Eqn. 2.

The probability of inter-marker confusion is now divided into two parts; the system dependent probabilities (noise, etc), and the component due to the distinctiveness of the markers themselves represented by the Hamming distance histogram. In this way, we can optimize, *i.e.* reduce, the probability of inter-marker confusion for any system by optimizing this histogram $HD(n)$. We seek to reduce the frequency of those of low values of n. The more that the histogram can be pushed out to the right (if plotted as in this paper), and the lower $HD(n)$ is for the first few (low n value) non-zero values of $HD()$, the more immune to inter-marker confusion a marker set will be.

$$P(\neq A) = \sum_{n=1}^{36} HD(n) \cdot p(n)q(n) \quad (1)$$

$$P(\neq A) = \sum_{n=1}^{36} HD(n) \cdot p^n(1-p)^{36-n} \quad (2)$$

This Hamming distance histogram will be different for each candidate symbol A. If the histograms are added together for all markers in the set, Eqns.1 or 2 can be used to find the probability that any marker in the set will be mistaken for any other marker in the set, giving a single probability of inter-marker confusion.

When applying Eqn.1, the first few non-zero entries (for low n) will dominate the calculated probability. This defines a measure of the total marker set to optimize: measure the Hamming distance between every possible marker and all others in all four possible rotation positions, aggregate this into a histogram of Hamming distances, and attempt to reduce the minimum non-zero value and area under the first part of the histogram.

This was done considering rotations and reflections between all possible combinations of markers to select the most optimal FEC polynomials and to select a subset of 2002 ID's from the possible range of 2046 [4], and to order them in a recommended list to aid in creating an application where less than the full 2002 markers are used.

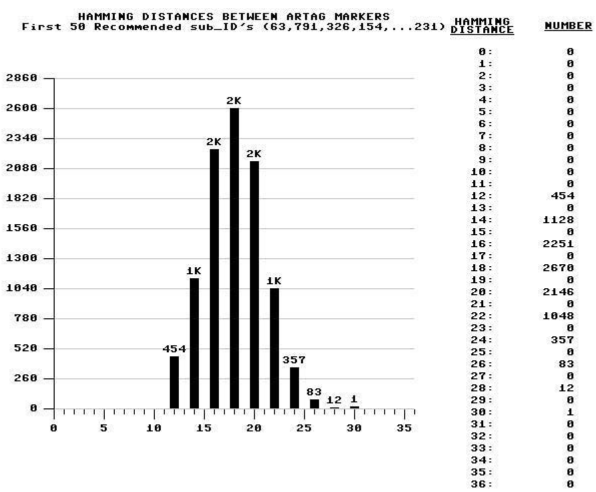

Figure 6. *Cumulative histogram of Hamming distances between markers considering rotation and reflection. Histogram considering the first 50 from the recommended list.*

5. Conclusions

A new marker system, called *ARTag* was created to improve upon existing marker systems based on passive vision of 2D planar markers. The quadrilateral border concept of ARToolkit was used along with a digitally encoded, error corrected ID code to replace ARToolkit's pattern recognition and identification step. ARTag has a library of 2002 unique ID markers without the need to load any pattern files. ARTag manages to achieve a low false negative rate comparable to ARToolkit, but has a vastly lower false positive error rate (0.0039%) and very low inter-marker confusion rate.

The ARTag system was designed to lower the probabilities of false positive detection and inter-marker confusion, as well as function under adverse lighting conditions and with occlusion. It is a robust system that solves the *correspondence problem* and can enable many applications such as AR where a camera or object pose is desired.

ARTag is available for download for evaluation [6] and free usage in non-commercial systems.

References

[1] *2003 IEEE / ACM International Symposium on Mixed and Augmented Reality (ISMAR 2003), 7-10 October 2003, Tokyo, Japan*. IEEE Computer Society, 2003.

[2] F. Xiao C. Owen and P. Middlin. What is the best fiducial? In *First IEEE International Augmented Reality Toolkit Workshop (at ISMAR)*, Sep 2002.

[3] D. Claus and Fitzgibbon. Reliable fiducial detection in natural scenes. In *Proceedings of the 8th European Conference on Computer Vision, Prague, Czech Republic*, May 2004.

[4] M. Fiala. Artag revision 1, a fiducial marker system using digital techniques. In *National Research Council Publication 47419/ERB-1117*, November 2004.

[5] I. Poupyrev H. Kato, M. Billinghurst. *ARToolkit User Manual, Version 2.33*. Human Interface Technology Lab, University of Washington, 2000.

[6] R. Hamming. Error detecting and error correcting codes. In *Bell Systems Technology Journal*, volume 29, pages 147–160, Apr 1950.

[7] H. Kato and M. Billinghurst. Marker tracking and hmd calibration for a video-based augmented reality conferencing system. In *Proc. the 2nd IEEE and ACM International Workshop on Augmented Reality*, pages 85–94, San Francisco, CA, USA, Oct 1999.

[8] V. Knyaz and A. Sibiryakov. The development of new coded targets for automated point identification and non-contact 3d surface measurements. In *Graphicon*, Moscow, Russia, 1998.

[9] L. Naimark and E. Foxlin. Circular data matrix fiducial system and robust image processing for a wearable vision-inertial self-tracker. In *ISMAR 2002: IEEE / ACM International Symposium on Mixed and Augmented Reality, Darmstadt,Germany*, Sept. 2002.

[10] A. S. Tanenbaum. *Computer networks*. Prentice-Hall, Inc, Upper Saddle River, NJ, 1988.

[11] X. Zhang, S. Fronz, and N. Navab. Visual marker detection and decoding in ar sytems: A comparative study. In *IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 97–106, Sep 2002.

[6] http://www.artag.net